Experimental analysis and predictive simulation of heat transport using TASK3D code

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Introduction I

- TASK3D [*] is an integrated transport code for helical plasmas and has been developed in collaboration between Kyoto Univ. and NIFS.

  [*]M. Sato et al., Plasma Fusion Res., 3, S1063 (2008).

- We have developed and incorporated into TASK3D:
  - neoclassical transport database module, DGN/LHD
  - radial electric field calculation module, ER.
- In order to simulate the NBI heated plasmas, FIT3D[**] code are incorporated into TASK3D.

  [**] S. Murakami, et al., Trans. Fusion Technol. 27 (1995) 256.

We can perform:

》self-consistent calculation of the heat transport and the distribution of heating power of the experimental plasmas (**Experimental analysis**).

》predictive simulations assuming a variety of NBI heating conditions (**Predictive analysis**).

- Using the improved TASK3D, heat transport simulations with several turbulent transport models have been performed to study LHD plasmas. ISHW(2009), IAEA(2010)

Introduction II

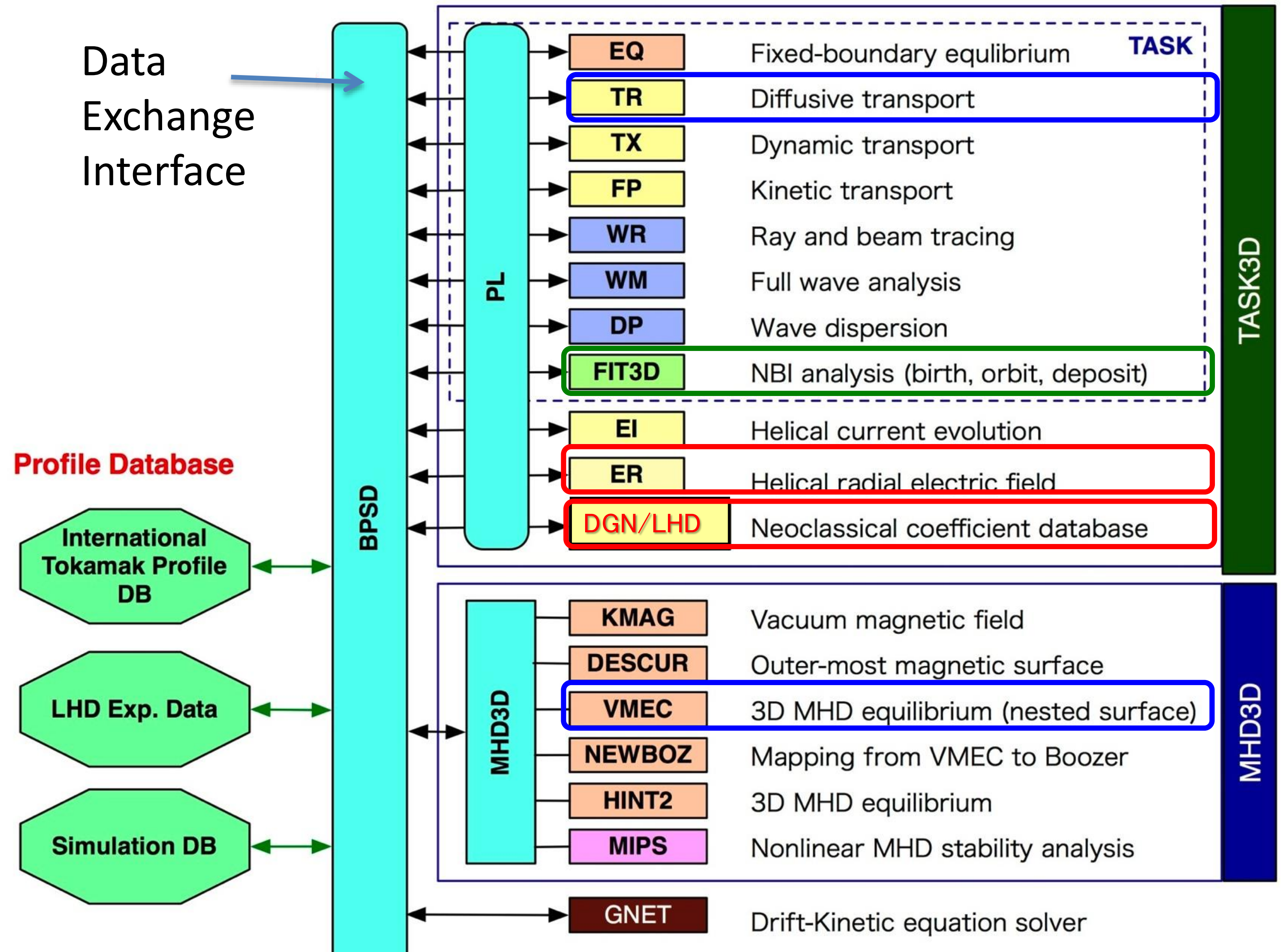
- In order to improve the accuracy of the turbulent transport model in TASK3D, we have made the comparison and the validation with LHD experimental results (14^{th}, Sep. 2011, EXP No. #773).
  - ≫ Determination of more appropriate value for Constant Factor, C_{model}.
  - ≫ validation of the turbulent transport model (gyro-Bohm, Bohm, and Alcator model).
  - ≫ introduction of the extended gyro-Bohm model which is included the temperature gradient factor.

  ISHW(2012), JIFT(2012), EPS(2012)

- Heat transport simulation in the time developing LHD plasmas
  A. Sakai (Kyoto Univ.), ITC22
- NBI heating analysis of time development plasma in LHD
  Yamaguchi(Kyoto Univ.), ITC22

Module Structure of TASK3D

- Each module, as shown here, describes different physical phenomena.
- Through the data exchange interface, each module is connected, and we can describe plasmas self-consistently.



TR
1D (radial) diffusive transport module

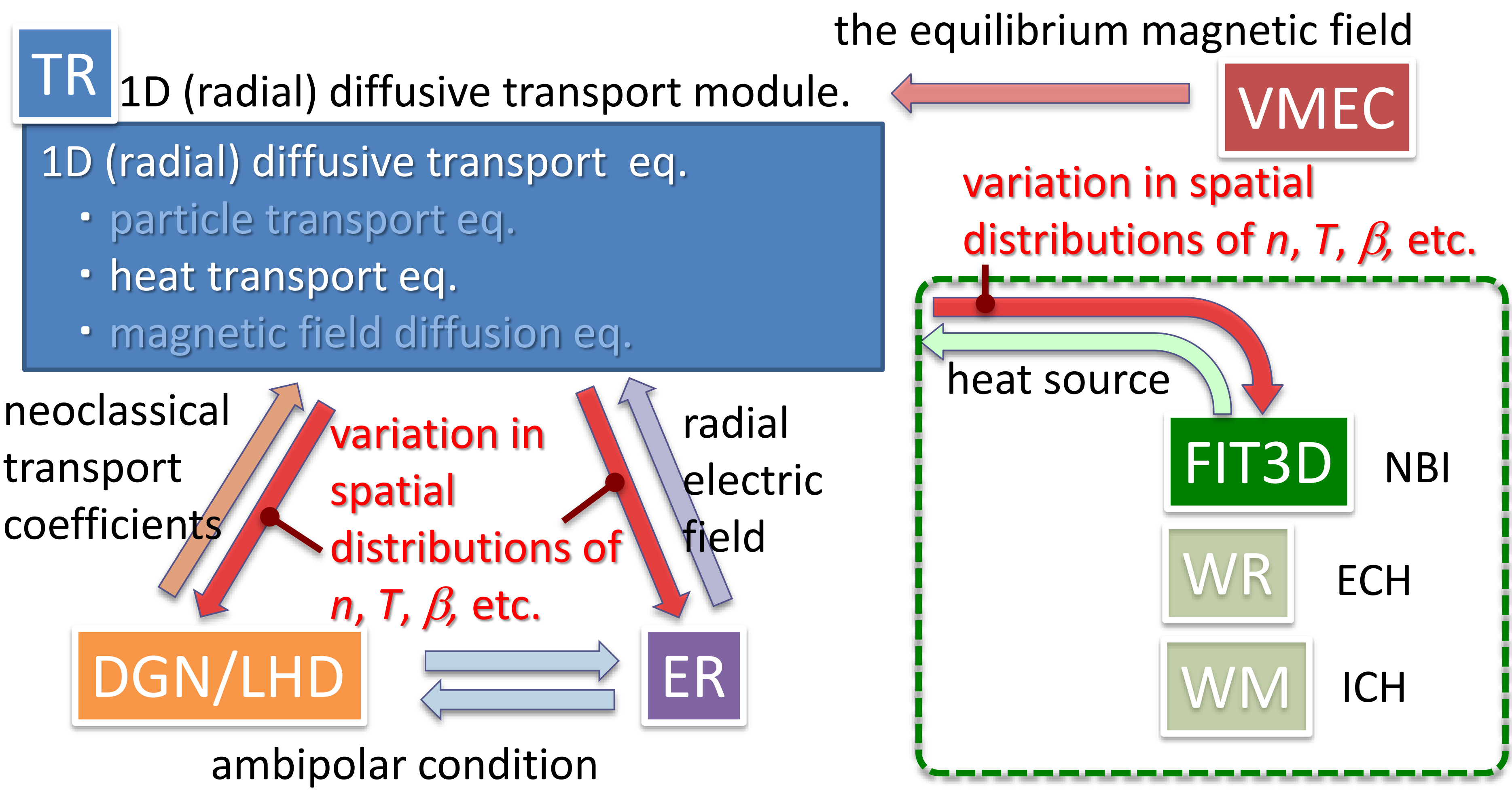
DGN/LHD
Neoclassical transport database module

ER
Radial electric field calculation module

FIT3D
NBI heating power calculation code

VMEC
3D MHD equilibrium calculation code

The Flow Diagrams of 1D Heat Transport Simulation using TASK3D



$$e\Gamma_e^{NC} = \sum Z_i e\Gamma_i^{NC}$$

The power deposition are calculated in response to change in spatial distribution of temperature and density in TR module.

Heat Transport equation: TASK/TR

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_sT_s\right) = -\frac{1}{V'}\frac{\partial}{\partial\rho}\left(V'\langle|\nabla\rho|\rangle n_sT_s\left(V_{K_s}+\frac{3}{2}V_s\right)-V'\langle|\nabla\rho|^2\rangle\left(\frac{3}{2}D_sT_s\frac{\partial n_s}{\partial\rho}+n_s\chi_s\frac{\partial T_s}{\partial\rho}\right)\right)+P_s$$

D_s : the particle diffusion coefficient χ_s: the thermal diffusion coefficient

V_s : the particle pinch velocity V_{Ks} : the heat pinch velocity

We assume that the transport coefficients are given as the sum of a neoclassical term and a turbulent term.

And we also assume the turbulent term of the electron and the ion are **equal.**

$$D_s = \boxed{D_s^{NC}} + \boxed{D_s^{TB}},\quad \chi_s = \boxed{\chi_s^{NC}} + \boxed{\chi_s^{TB}},\quad V_s = \boxed{V_s^{NC}} + \boxed{V_s^{TB}},\quad V_{K_s} = \boxed{V_{K_s}^{NC}} + \boxed{V_{K_s}^{TB}}$$

NC, neoclassical transport coefficient: neoclassical transport database, DGN/LHD.

TB, turbulent transport coefficient : the turbulent transport models.

In this study, we consider the turbulent term is only χ^{TB}. ($D_s^{TB}=V_s^{TB}=V_{Ks}^{TB}=0$) .

	Bohm model emphasized on the edge region	gyro-Bohm model	Alcator Scaling model	advanced gyro-Bohm model (Including the effect of grad T)
χ^{TB}	$C_{edgeBohm}\frac{T}{eB}\left(\frac{r}{a}\right)^2$	$C_{gyroBohm}\frac{T}{eB}\left(r\frac{L}{a}\right)$	$C_{1/n}\frac{1}{n}$	$C_e^{(0)}\frac{1}{16}\frac{T_e}{eB}\frac{r_i}{a}+C_e^{(1.5)}\frac{1}{16}\frac{T_i}{eB}\frac{r_i}{a}\left(\frac{\nabla T_i}{T_i}a\right)^{\frac{3}{2}}$
				$C_i^{(1.5)}\frac{1}{16}\frac{T_i}{eB}\frac{r_i}{a}\left(\frac{\nabla T_i}{T_i}a\right)^{\frac{3}{2}}$

In each model, the C_{model} is a constant factor.

Reference Plasmas

Shot num.	time[sec]	Rax[m]	B_0[T]	T_{e0}[keV]	T_{i0}[keV]	$n_0[10^{19}m^{-3}]$
the 15 cycle exp. (EXP No. #773, 14 SEP 2011)						
109081	4.24	3.60	2.75	3.0	3.0	3.07
109082	4.24	3.60	2.75	3.2	3.5	2.78
109125	4.24	3.60	2.85	3.4	4.1	1.81
109129	4.24	3.60	2.85	3.4	3.8	2.63
109131	4.24	3.60	2.85	3.4	4.0	2.27
109133	4.24	3.60	2.85	3.4	3.8	2.61
109134	4.24	3.60	2.85	3.3	3.5	2.87
109135	4.24	3.60	2.85	3.3	3.4	2.99

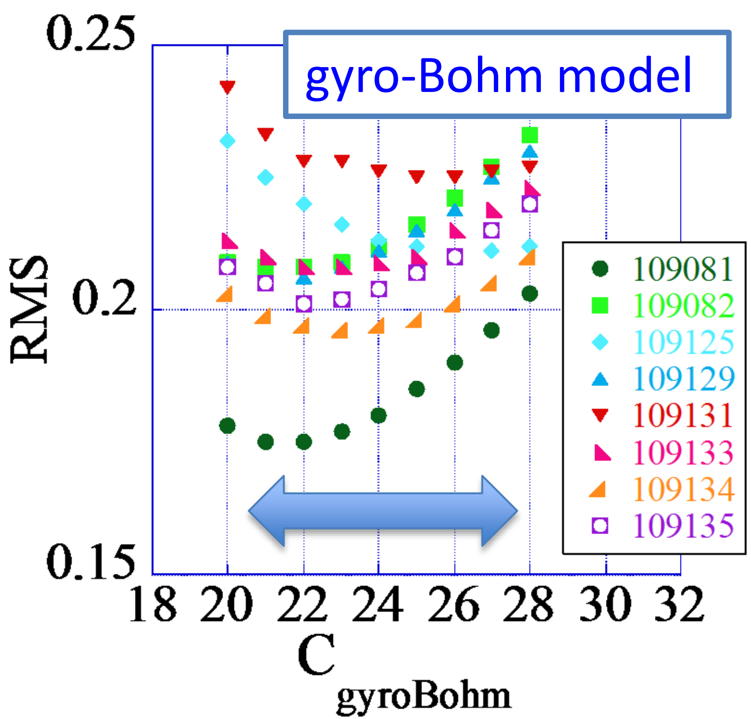
Determination of the Constant Factor, C_{model}

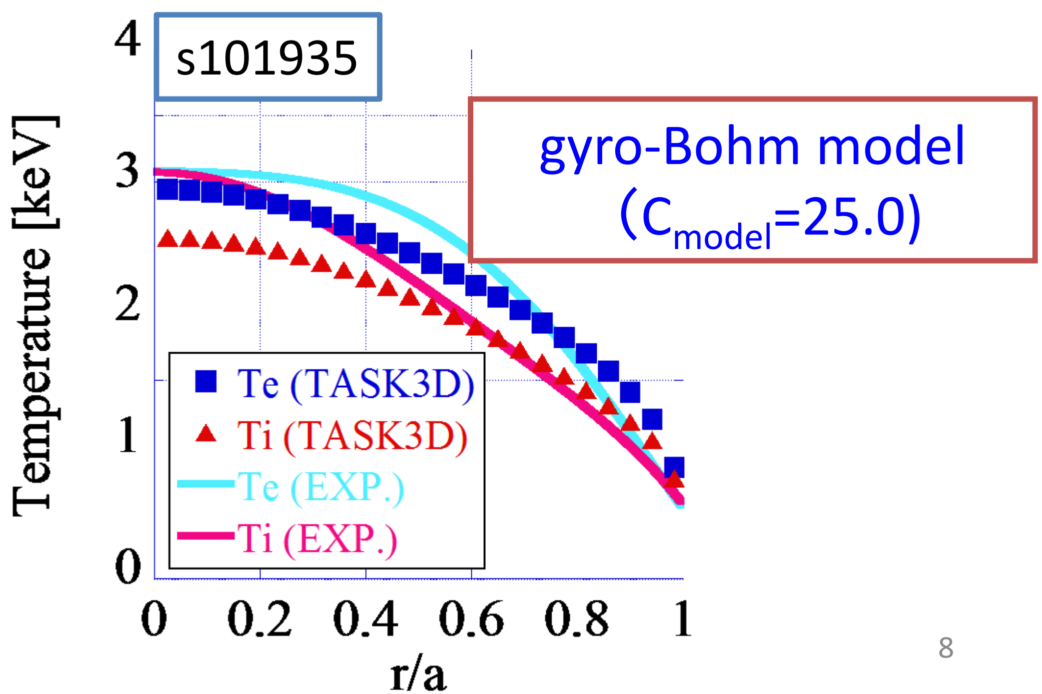
The factor C_{model} are determined so as to minimize RMS values.

- We show the results in the case of assuming the gyro-Bohm model.

Calculating the RMS values with the various values of C_{model} in reference shots, the C_{model} values which minimize the RMS are distributed from 22 to 27.

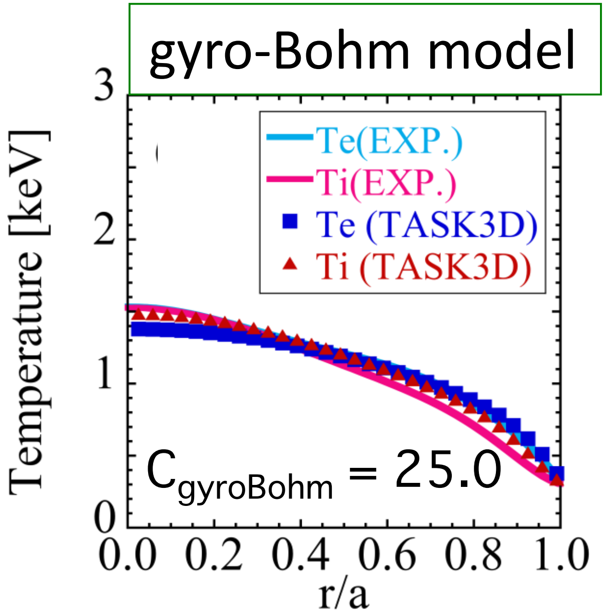
- We decide the C_{model} value to 25 to minimize the summation of these RMS values.
- In this case, the averaged error between the experimental results and TASK3d results are about 20%.

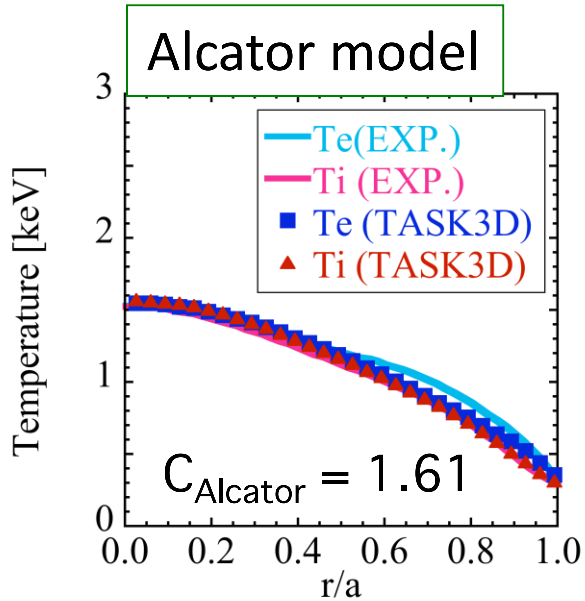


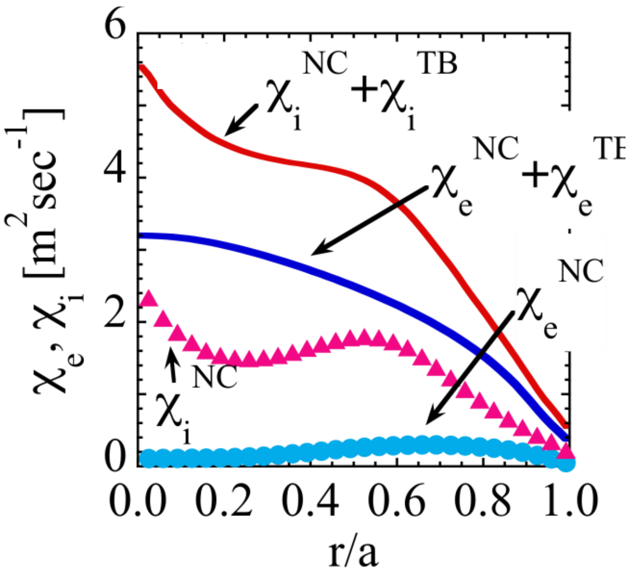


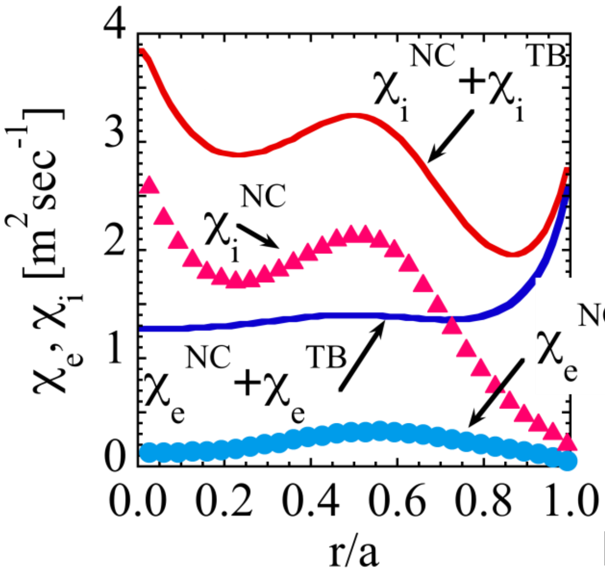
Heat Transport Analysis using TASK3D

s88343: 1.833sec, R_{ax}= 3.6m, B_0 = 2.75T, β_0 = 0.11%









The ratio between the turbulent and the neoclassical transport coefficient is :

electron : factor $\approx$ 10

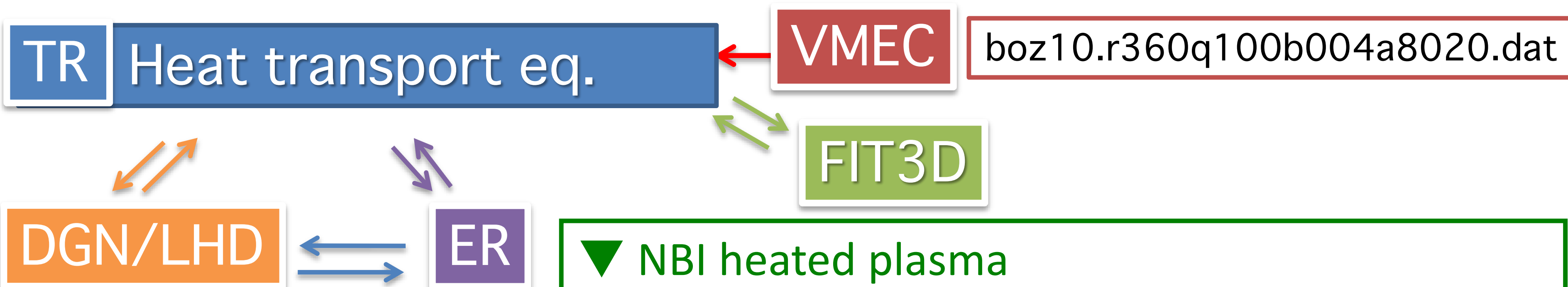
ion: factor $\approx$ 0.5 - 1

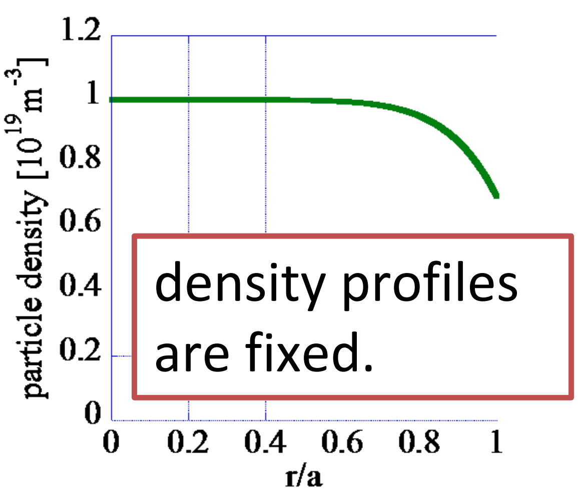
It is found that:[*]
the anomalous transport dominates in the electron thermal transport and the neoclassical transport plays an important role in the ion thermal transport.

[*]A. Wakasa, et al,. IAEA2010

Predictive Simulation Results of NBI Heated Plasma

We applied TASK3D to predictive heat transport simulations for the LHD experiment with R_{axis}=3.6m and B_0=-2.85T.
In this simulation, we assume the turbulent transport model as per the gyro-Bohm model with Cgyro-Bohm=25.0.





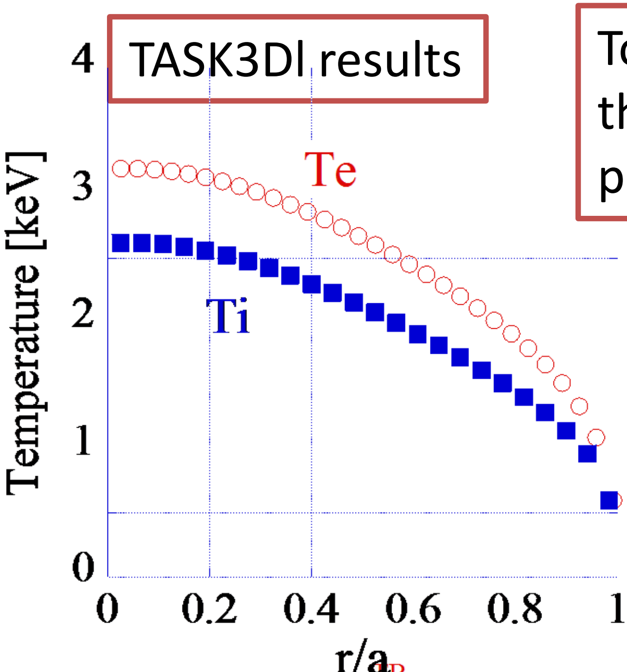
density profiles are fixed.

▼ NBI heated plasma

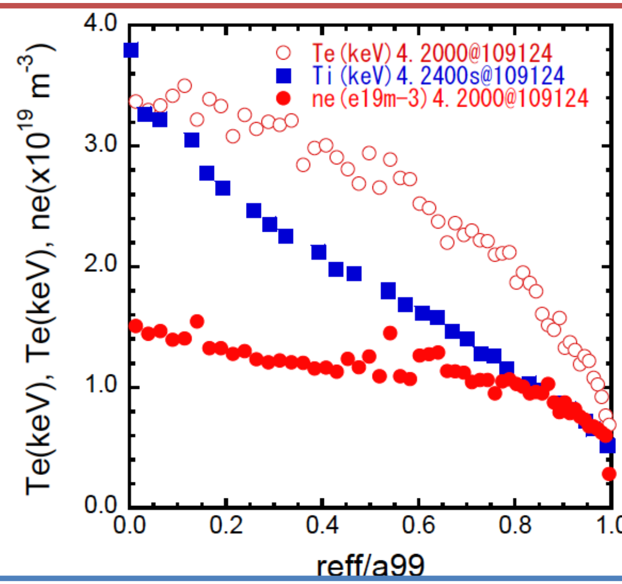
Each NBI power of port through is considered as:
#1(5.8MW), #2(4.5MW), #3(4.5MW), #4(4.5MW), and #5(6MW).

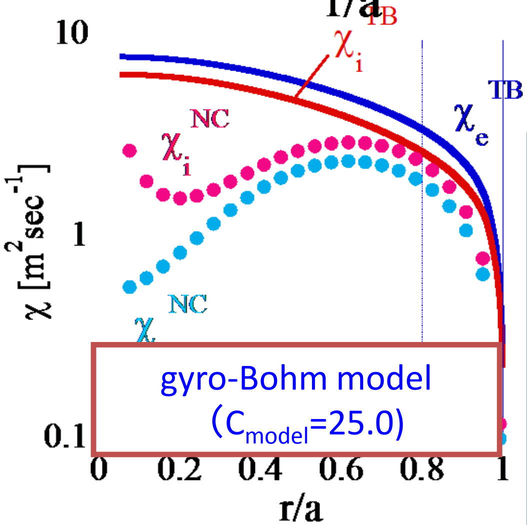
We calculate the NBI power deposition along with the time evolution of electron and ion temperatures until the steady state.

Results of the Predictive Simulation of NBI Heated Plasmas



To validate the simulation results, the LHD experiments in the similar NBI heating condition and density profiles were performed (below).





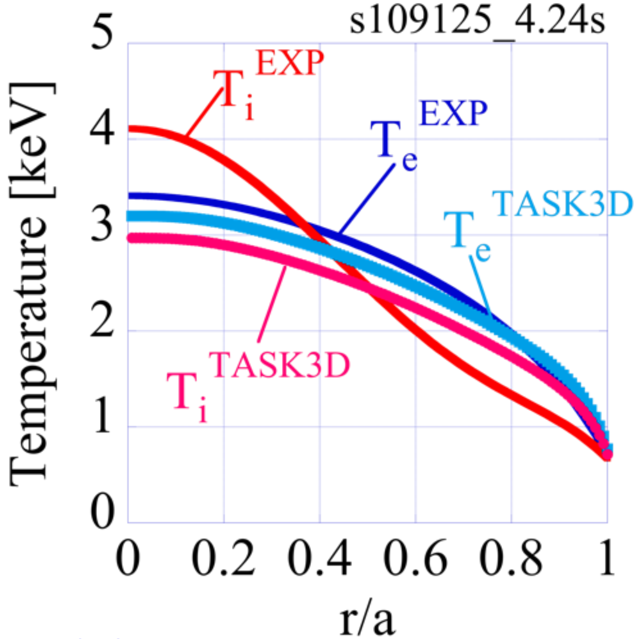
The electron temperatures obtained by the predictive simulation are in good agreement with the experimental results($Te(r/a=0) \simeq 3.2$keV and parabolic profile), and

the ion temperatures in the experiment are about 25% higher then the predictive simulation results in the core region.

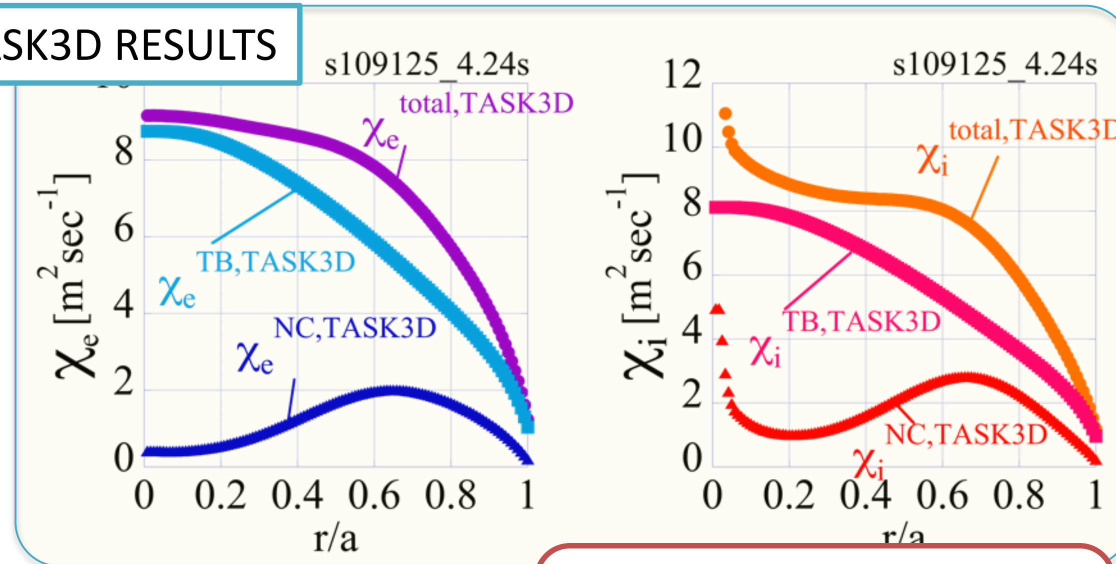
Comparison between Simulation and Experimental Results

gyro-Bohm model

$c_e^{TB} = c_i^{TB}$ is assumed.

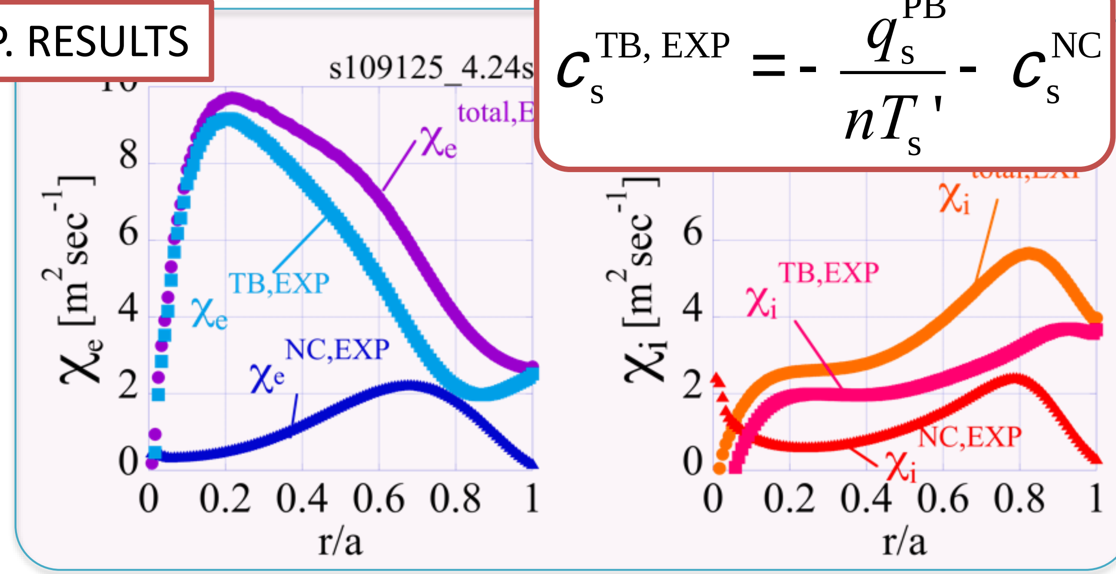


TASK3D RESULTS



EXP. RESULTS

$$c_s^{TB,\ EXP} = -\frac{q_s^{PB}}{nT_s'} - c_s^{NC}$$



T_e^{TASK3D} agrees well with T_e^{EXP}.

BUT…

T_i^{TASK3D} disagrees with T_i^{EXP}.

Core: $T_i^{TASK3D} < T_i^{EXP}$

Edge: $T_i^{TASK3D} > T_i^{EXP}$

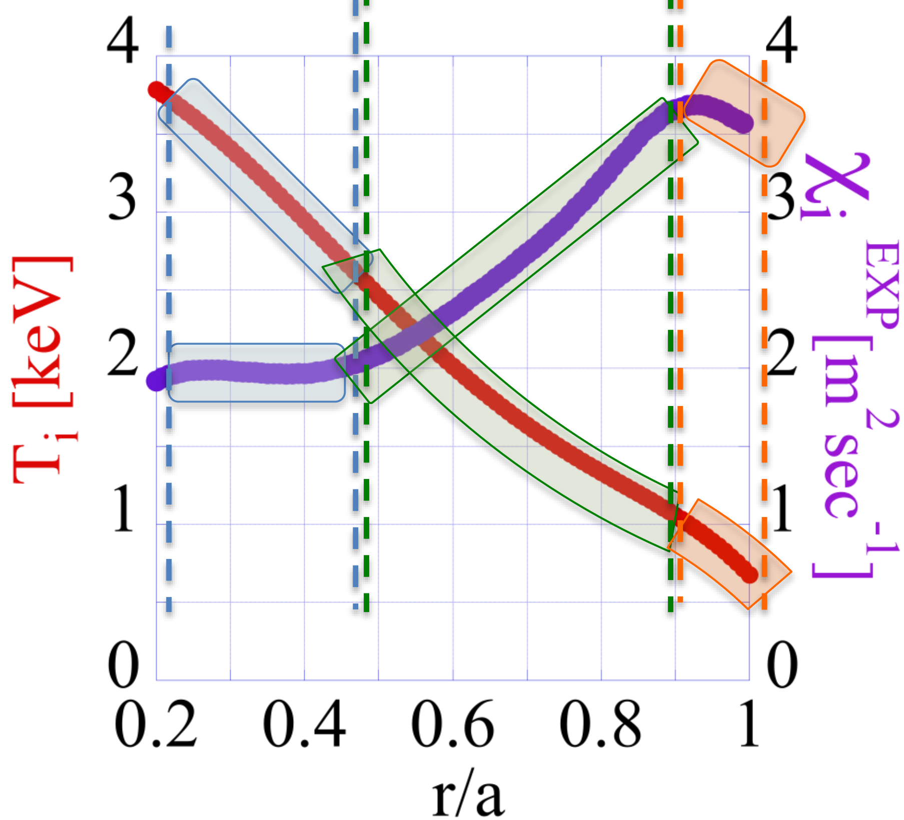
$\chi_e^{TB,TASK3D}$ agrees with $c_e^{TB,EXP}$.

$\chi_i^{TB,TASK3D}$ disagrees with $c_i^{TB,EXP}$.

χ_e^{TB} and c_i^{TB} is **not equal.**

Interrelation between gradient T_i and χ_i

$\frac{\partial^2 T_i}{\partial r^2}=0$	$\frac{\partial^2 T_i}{\partial r^2}>0$	$\frac{\partial^2 T_i}{\partial r^2}<0$
$\frac{\partial \chi_i}{\partial r}=0$	$\frac{\partial \chi_i}{\partial r}>0$	$\frac{\partial \chi_i}{\partial r}<0$



Suppose the thermal diffusivity is to proportional to the temperature gradient.

$$\frac{\partial \chi_i}{\partial r} \propto \frac{\partial^2 T_i}{\partial r^2}$$

$$\boxed{\chi_i \propto \frac{\partial T_i}{\partial r}}$$

We include the temperature gradient factor, aT'/T, to the gyro-Bohm model as :

$$\chi_i^{\mathrm{TB}} = C_{\mathrm{gyroBohm}\times\mathrm{gradT}}\, gB \times \boxed{\left(\frac{\partial T}{\partial r}\frac{a}{T}\right)}$$

Gyro-Bohm Transport Models
Including the Effect of Temperature Gradient

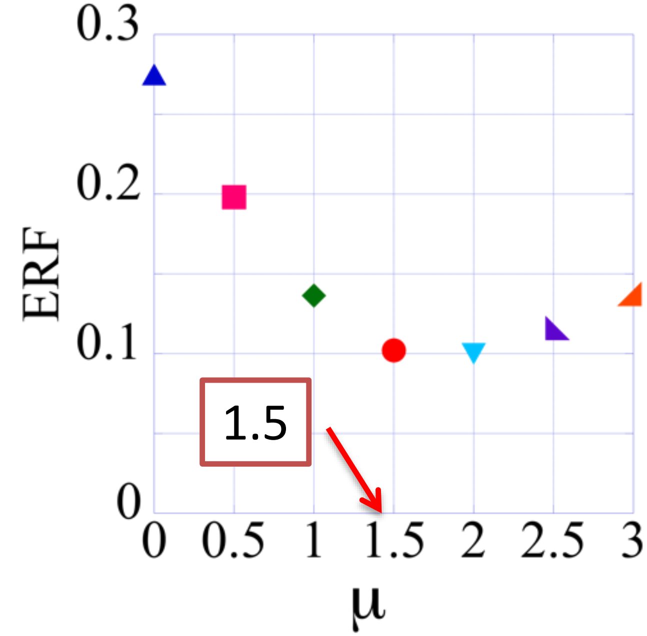
We consider the effect of the temperature gradient on the heat transport and include the temperature gradient factor, aT'/T, in the gyro-Bohm model.

$$\chi_i^{\mathrm{TB}} = \mathrm{C_i} \times \mathrm{gB} \times \left(\frac{T'}{T} a\right)^{m}$$

Here, *m* is the index to measure the effect of the grad *T* term in turbulence transport.

In the case of *m*=1.5, RMS value is minimized.
(using grad T to the 1.5th power is similar to the CDIM model [*])

[*] K. Itoh, S. -I. Itoh and A. Fukuyama, Phys. Rev. Lett. Vol. 69 (1992) 1050



not Including the Effect of Temperature Gradient

Including the Effect of Temperature Gradient

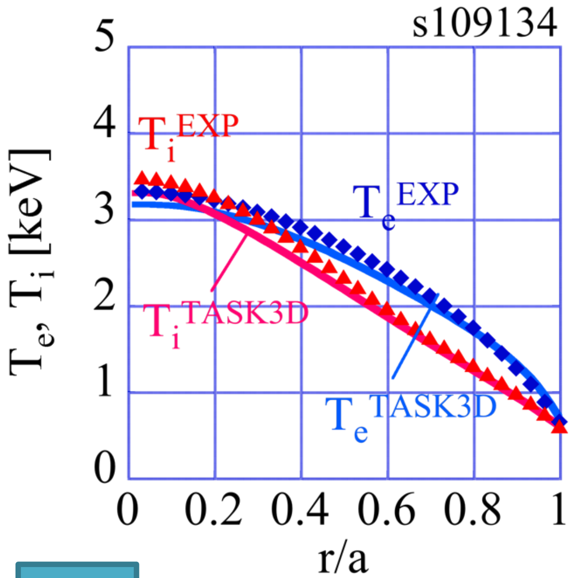
$$\chi_e = \boxed{\mathrm{C_e^{(0)}} \frac{1}{16}\frac{T_e}{eB}\frac{\rho_i}{a}} + \boxed{\mathrm{C_e^{(1.5)}} \frac{1}{16}\frac{T_i}{eB}\frac{\rho_i}{a}\left(\frac{\nabla T_i}{T_i} a\right)^{\frac{3}{2}}} \qquad \chi_i = \boxed{\mathrm{C_i^{(1.5)}} \frac{1}{16}\frac{T_i}{eB}\frac{\rho_i}{a}\left(\frac{\nabla T_i}{T_i} a\right)^{\frac{3}{2}}}$$

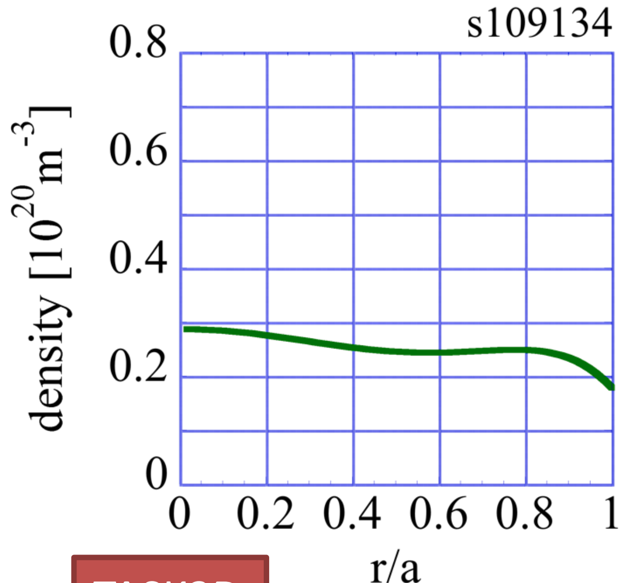
simple gB

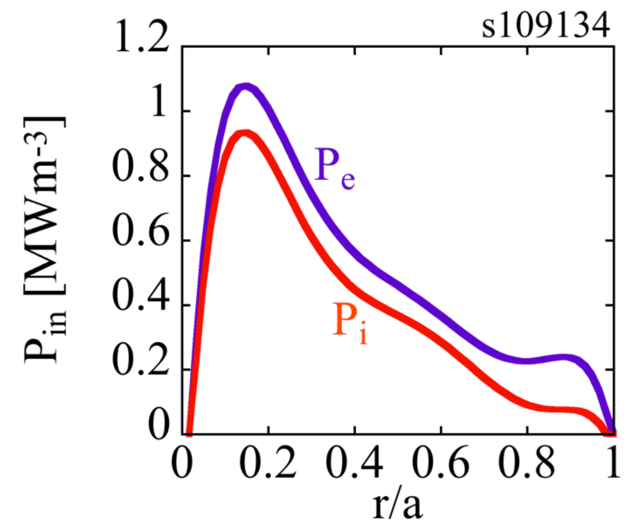
gB x grad T_i

gB x grad T_i

Simulation Results Using the Gyro-Bohm Models Including the Effect of Temperature Gradient - s109134,4.20sec,B=+2.750T,NBI#1#2#3#4#5 -



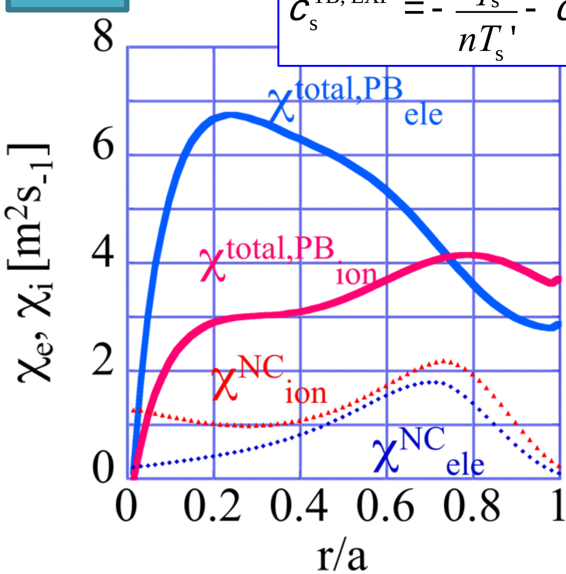


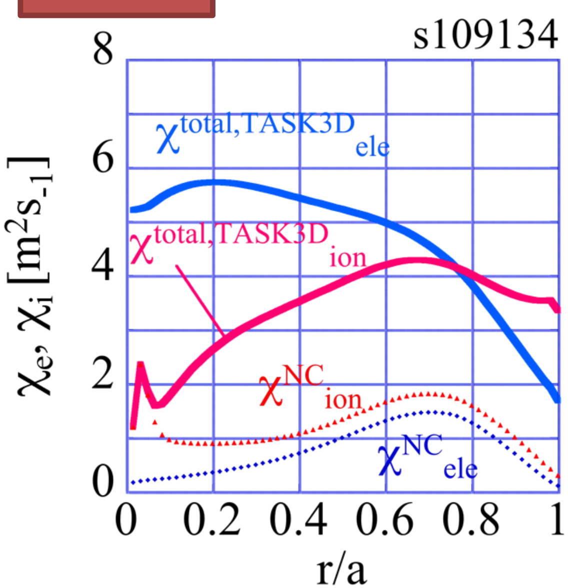


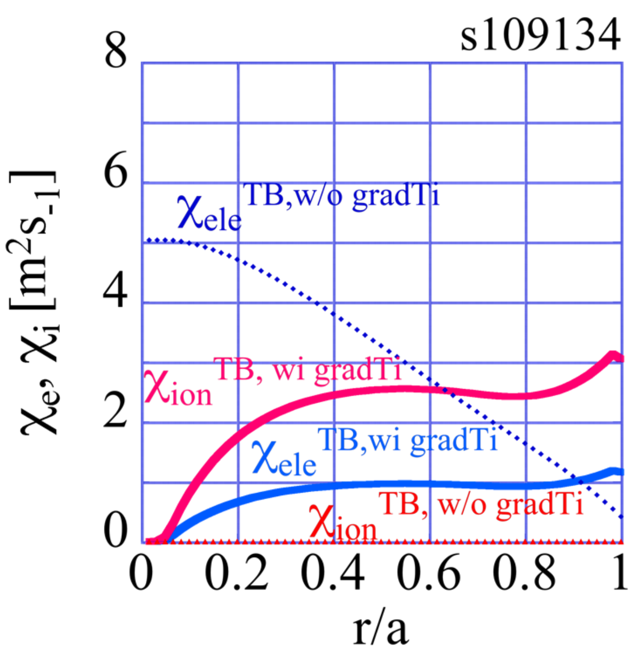
EXP.

$$c_s^{TB,\,EXP} = -\frac{q_s^{PB}}{nT_s'} - c_s^{NC}$$

TASK3D



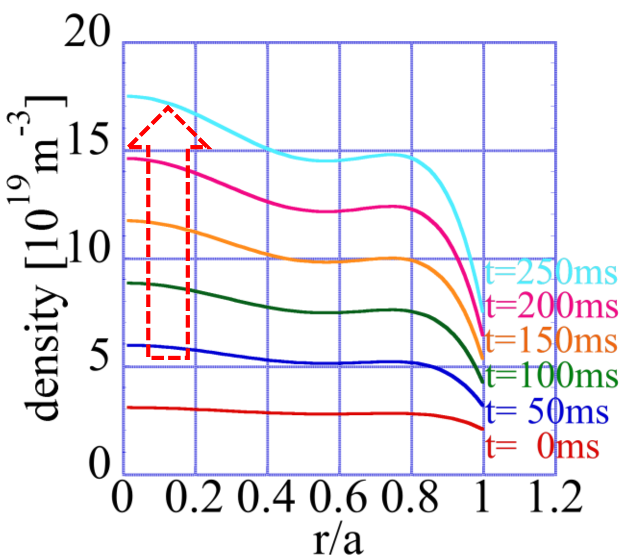


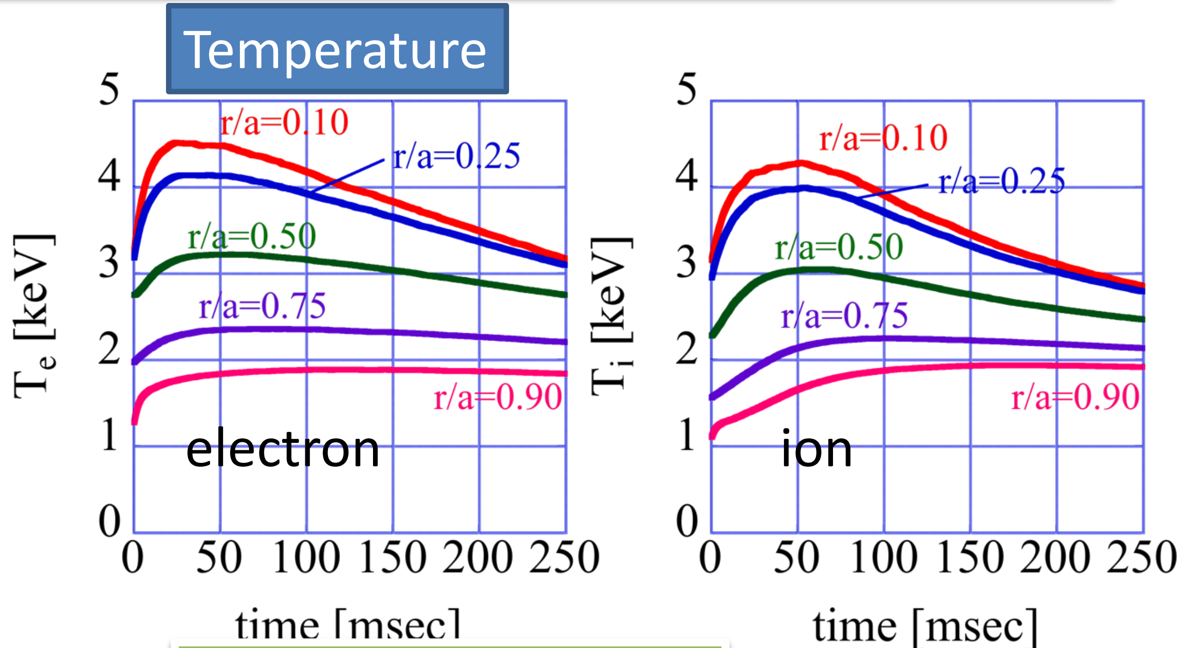


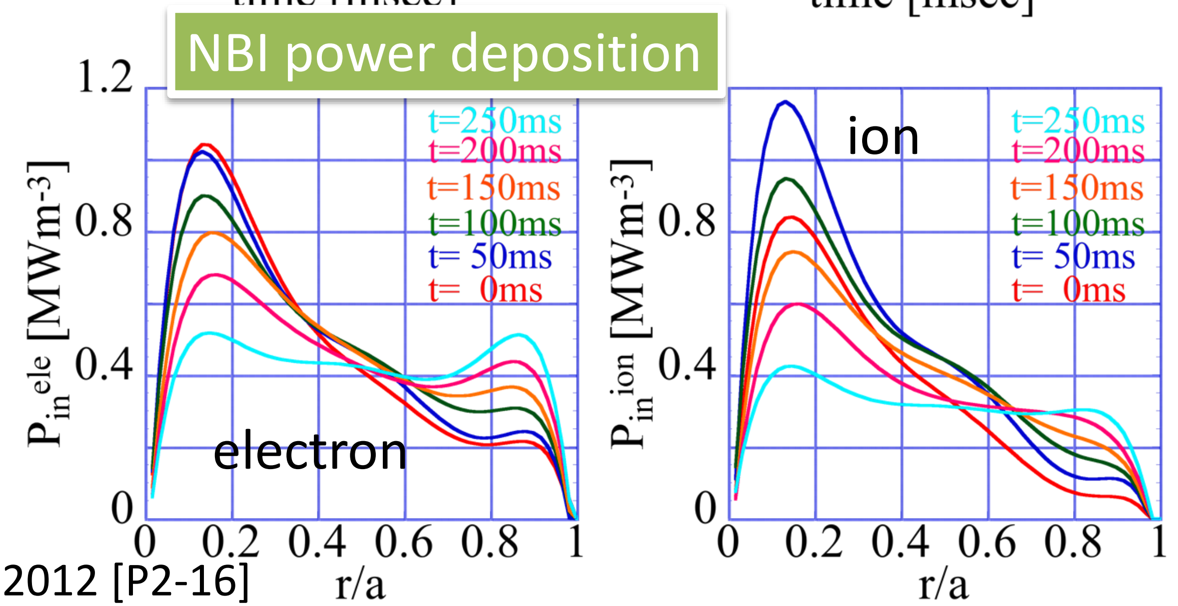
Heat transport simulation in the time developing LHD plasmas[*]

We perform the predictive simulations assuming the time evolution of the density.

- The density is increased up to 10 times during the 250 msec.







[*]A. Sakai, et al. ITC22, Toki, Nov. 20,2012 [P2-16]

Summary I

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  - We have developed and incorporated into TASK3D:
    - neoclassical transport database, DGN/LHD[1-2]
    - radial electric field calculation module, ER
    - NBI heating power calculation code, FIT3D
  - Using the TASK3D, we have performed [4-5]:
    - self-consistent calculation of the heat transport and the distribution of heating power of the experimental plasmas (**Experimental analysis**).
    - predictive simulations assuming a variety of NBI heating conditions (**Predictive analysis**).
- Heat transport simulations with several turbulent transport models have been performed to study LHD plasmas [3,4].
    - **The turbulent transport dominates in electron thermal transport.**
    - **The neoclassical transport plays an important role in the ion thermal transport.**

Summary II

- In order to reproduce the ion temperature distribution, We consider the improvement of the gyro-Bohm model[7].
  - We include the temperature gradient factor, aT'/T, in the gyro-Bohm model.

$$\chi_{\rm e} = \boxed{C_{\rm e}^{(0)} \frac{1}{16} \frac{T_{\rm e}}{eB} \frac{\rho_i}{a}} + \boxed{C_{\rm e}^{(1.5)} \frac{1}{16} \frac{T_{\rm i}}{eB} \frac{\rho_i}{a} \left(\frac{\nabla T_{\rm i}}{T_{\rm i}} a \right)^{\frac{3}{2}}} \qquad \chi_{\rm i} = \boxed{C_{\rm i}^{(1.5)} \frac{1}{16} \frac{T_{\rm i}}{eB} \frac{\rho_i}{a} \left(\frac{\nabla T_{\rm i}}{T_{\rm i}} a \right)^{\frac{3}{2}}}$$

  - By including the effect of grad T, TASK3D simulation reproduces both the electron and ion temperatures for LHD plasmas.

[1] **A. Wakasa**, *et al.*, 51st Annual Meeting of APS-DPP (2009).
[2] **A. Wakasa**, *et al.*, in Proc. ISHW (2009).
[3] **A. Wakasa**, *et al.*, Contrib. Plasma Phys. 50, No. 6-7 (2010).
[4] **A. Wakasa**, *et al.*, in Proc. 23rd IAEA FEC (2010).
[5] **A. Wakasa**, *et al.*, 53rd Annual Meeting of APS-DPP (2011).
[6] **A. Wakasa**, *et al.*, ISHW2012
[7] **A. Wakasa**, *et al.*, EPS2012